RESEARCH ARTICLE

Electron Beam Welding: Heat Flow Model including Peclet Number

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ABSTRACT

Electron beam welding is recognized as a low heat input for obtaining thinnest bead width and longest weld penetration among the technologies to provide low distortion. The challenge is to keep the electron beam focused without distractions to surroundings which is obtained by performing the process in a vacuum chamber. EBW modeling is similar to laser weld in terms of heat flux flow with a surface heat on bead area in the form a Gaussian distribution. When the beam forms a keyhole, the heat is conducted to the base metal by a frustum distribution. As there is no blind end at the bottom, a portion of the heat would leave out to ambience through the lower end of the bead. The heat flow mechanism is calculated using Peclet number from where the empirical formulae power distribution is determined. Peclet number variation is calculated as a function of radial distance, penetration depth and distance from wall. A method for incorporating weld velocity and gas flow in simulation and modeling is also discussed. Finite element analysis is done and temperature graphs were obtained for welding using Ansys software. Weld material used is SS304 and temperature dependent thermal and structural properties are considered. The output obtained is the thermal isotherms around the weld to estimate the fusion, bead and heat effected zones.

Keywords: Electron beam welding, Laser weld, Gaussian distribution, Frustum distribution, Peclet number.

1. INTRODUCTION

Electron beam welding is one of the high power densities and low heat input weld processes which results in low distortions and narrow heat affected zone in the welds with good mechanical properties. Fusion reactor components and other nuclear structures are demanding applications with EBW process. Still beam process oriented stress and temperature data explores more insight in improving the structural properties of the welds. The basics of electron beam welding and it's comparison with laser beam welding with different manufacturing techniques are given in the collection of articles compiled [1, 2]. The demand for electron beam welding process is studied extensively and the initial model of keyhole was given [3-9]. The process of electron beam welding was modelled using finite element method which also gave simulation of welding process. Residual stress measurement has also been described [10-14].

In this paper, the distribution of heat partly by conduction and convection in the plasma fluid flow is simulated and shown with results using a finite element process. Similarity laser beam welding is discussed and, Peclet number data along with ANSYS simulation to predict the temperature and stress information on 5mm thick SS304 plate EB welds are performed.

2. ELECTRON BEAM WELDING PROCESS

In this process, a high density electron beam is generated and sent into the fusion zone between the two parts to be welded. Alike laser beam welding process, the initial transfer of energy is from the surface, subsequently the electrons penetrate into the weld pool. The parts are moved with the desired velocity to

obtain the correct weld bead. [15] The beam generates heat and initially the conduction mode transfers it to the parts and melts them. High energy vaporises the molten metal and a fume is formed to encompass the electrons. The trapped energy laterally moves into the parts. The formation of entrapped beam in the keyhole is shown in figure A1 with the length equal to the plate thickness to be welded and the bottom width is root gap, where the top is the weld bead width.

2.1. Thermal model

A thermal solution is derived from the quasi-static state technique. A non-linear thermo mechanical FE analysis is performed and enhanced with user subroutines. The governing partial differential equations for the transient heat flow is given as in equation (2.1),

$$K(T)\left(\frac{\partial 2_T}{\partial x^2} + \frac{\partial 2_T}{\partial y^2} + \frac{\partial 2_T}{\partial z^2}\right) + Q = \rho(T)C_p(T)\frac{\partial T}{\partial t} \quad (2.1)$$

where x, y, z are the Cartesian co-ordinates and Q is the internal heat generation. The temperature dependent thermal parameters of conductivity $(K(T))$, density $(\rho(T))$ and specific heat $(C_p(T))$ are used in the heat equation. This equation gives the balance of heat generation and conduction of the system and is solved for different boundary conditions.

In the analysis, the absorbed energy from the electron source is assumed as 70% in the key hole which is taking a frustum shape of heat flux distribution compared to 30% Gaussian distribution of heat flux distribution from the surface of bead. For convection simulation thermal dependent convective heat transfer coefficient $(h(T))$ and radiation heat transfer, Stephen Boltzmann's constant $\sigma = 5.67E^{-8}$ and emissivity (ε) of surface are specified. A combined radiation and convection convective heat transfer coefficient (h_r) is defined and used for hot rolled steel plates with less than 3% error. Thermal analysis is carried out with constant heat flux, where thermal load is applied constantly for 10 seconds and gradually increased up to 1000 seconds and then the plate is allowed to cool down to ambient temperature.

2.1.1. Peclet number

The Peclect number named after the French physicist Jean Claude Eugene Peclet is a dimensionless number relevant in the study of transport phenomena of fluid flows. It is adapted to welding as molten metal flows and exhibits fluid flow characteristics. Peclet number is equivalent to the product of Reynolds and Prandtl number of mass transfer. Mass and thermal diffusion are defined when Peclet number is the product of the Reynolds and Schmidt number as shown in equation (2.2)

$$P_e = \frac{\text{heat convection}}{\text{heat conduction}} = \frac{u\rho c_{pL_R}}{K} \quad (2.2)$$

where L is the characteristic length and U refers to the velocity. Peclet number indicates the heat distribution due to convection and conduction of the welding process in the molten metal.
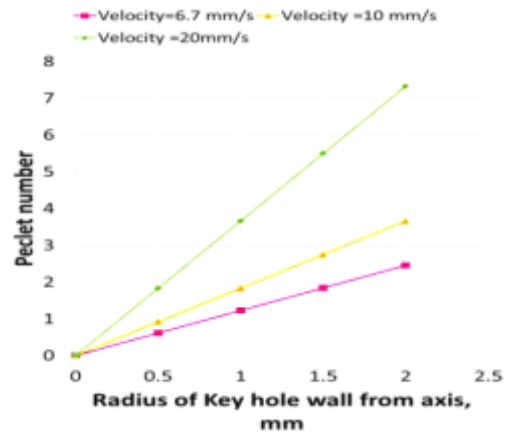

Figure 1.Change in Peclet number with keyhole radius and molt velocity

In this study, the variation of Peclet number is studied for different flow velocities, 6.7, 10 and 20mm/s, as in figure 1. When molten metal is static, Peclet number is zero. Hence the convection linearly increases with radius from the bead axis and also with the flow velocity.
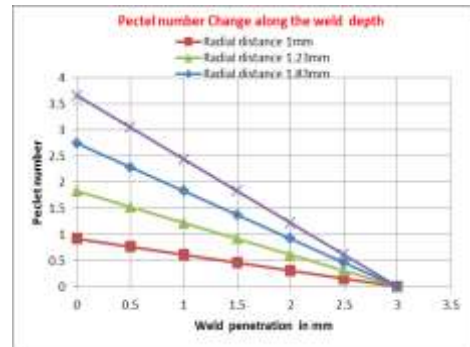

Figure 2.Peclet number with Weld penetration and radial distance

Peclet number is the greatest on the surface of weld as given in figure 2. This results in increased convection. For the same reason, as the bead radius increases Peclet number increases by 1mm when surface Peclet number is 1, in where the convection and conduction are same and increases to 3.7 when radial distance is 2mm, that is convection is 3.7 times the conduction. The amount of heat in the keyhole is assumed to be proportional to the Peclet number which can be determined for specific bead radius and penetration.
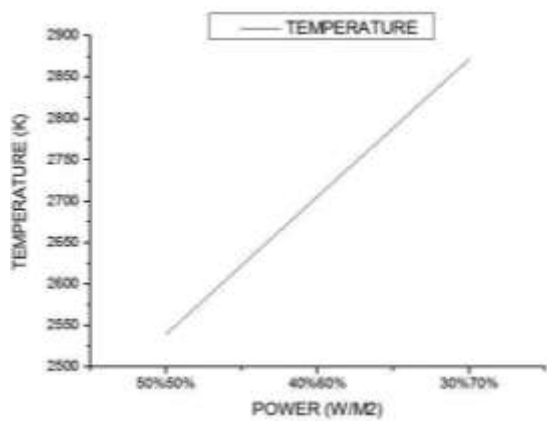
2.1.2. Finite element method

Figure 3.Ratio of Power on surface convection to power lateral conduction

To solve the heat transfer problem, temperature at bead area is calculated for the welding process using different Peclet numbers as given by three ratios of convection to conduction of 50%/50%, 40%/60% and 30%/70% accordingly. These ratios of heat flux distribution were given on weld surface (Gaussian distribution) and on the keyhole area as lateral heat load (frustum distribution). The weld zone temperatures are shown in figure 3.

2.2. Finite Element Method (FEM)

Ansys package is used for analysis. Figure 4 shows the 8 nodded brick element.
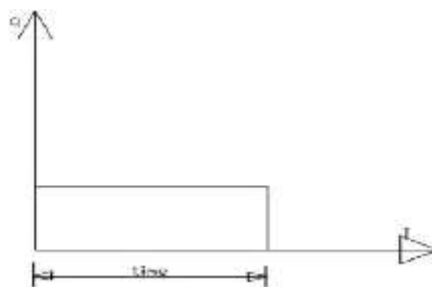

Figure 4.8 nodded brick element

Figure 5 gives the plate model to be welded. As symmetric model is assumed in geometric, load and boundary conditions, only one part is analyzed. Finite element model as shown in figures 6 and 7 represent the temperature distribution in Kelvin. This is for a 50%/50% distribution which gives about the maximum of 2580K. The temperature distribution with time is shown in figure 8. It can be seen that the peak temperature is reached in a short period of about 40 seconds but cooling back to ambient temperature takes more than 1000 seconds.
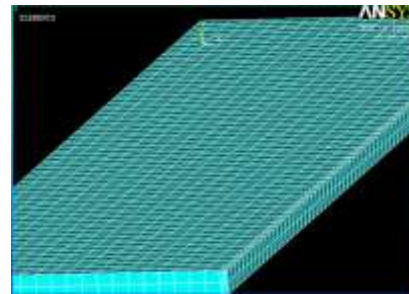

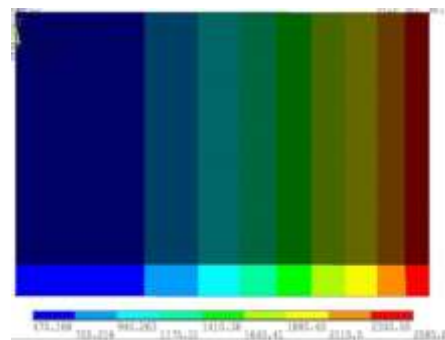Figure 5.Plate to be welded

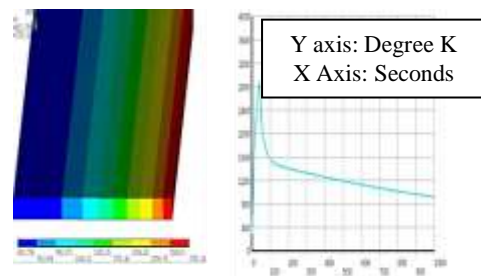Figure 6.Finite element model

Figure 7.Temperature distribution

Y axis: Degree K
X Axis: Seconds

Figure 8.Temperature distribution with time at weld bead

3. CONCLUSION

- FEM simulation by adapting a constant heat flux analysis has been carried out on SS 304 steel materials for the transient thermal temperature.
- The temperature at fusion zone and also at face of the model is compared with all heat fluxes given and the variation of the temperatures changes in the bead and in the face of the power variations is improved in the weld-ability of the depth of the model.
- Peclet number prediction and indirect analysis can be correlated with the thermal properties and stress of the actual material in the EBW process effectively.
- The temperature field at the weld zone was found to be higher at the given constant heat flux input when compared with the heat affected zone and base plate regions.
- This prediction of analysis with reference to the estimation of thermal analysis will be useful to predict the weld stresses and can be implemented for the fabrication process and analysis of the reactor grade component design requirements.

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APPENDIX
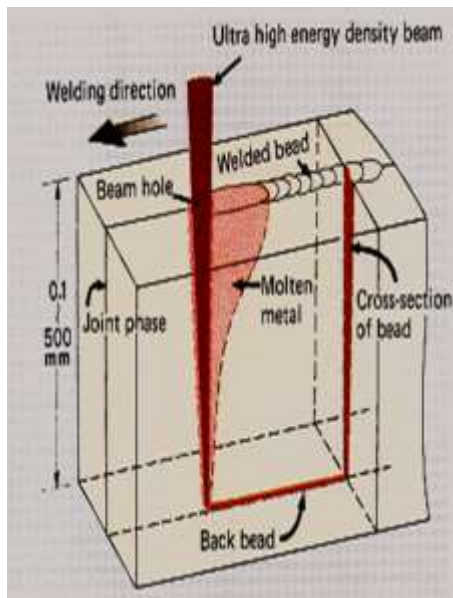
Electron beam welding, the plasma keyhole play crucial role in the weld bead
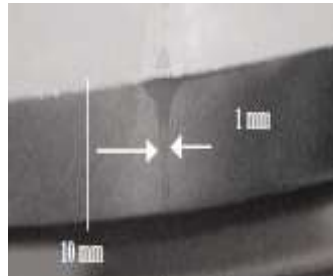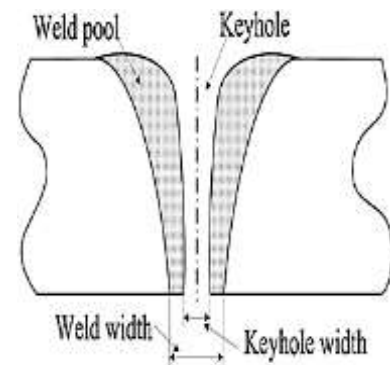
Very narrow weld bead and narrow HAZ are the significant characteristics of EBW process.

Figure A1.Electron beam welding process

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